Report of the Working Group on Digital Mammography: Digital Displays and Workstation Design

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Introduction

Breast cancer is the most commonly diagnosed cancer and the second leading cause of cancer deaths among American women. Today, one in eight women in this country will develop breast cancer. In spite of extensive research in breast cancer prevention and treatment, early detection of breast cancer through imaging remains the best hope that women currently have for effective treatment and reduced mortality. Conventional X-ray mammography, a mature technology providing high quality images at low radiation dose, has been shown to reduce mortality of breast cancer by about 30% in women older than 50 years of age and by about 17% in younger women. However, recent data indicate that many women have radiodense breast tissue, making conventional diagnosis problematic. Three out of four lesions detected by conventional mammography are benign, resulting in unnecessary biopsies and other medical procedures. These limitations in conventional mammography have created a strong incentive for the development of novel imaging technologies for improved early detection of breast cancer.

In 1991, National Cancer Institute (NCI) convened a conference devoted to the review and development of a research agenda for novel breast imaging technologies. This conference unanimously recommended digital X-ray mammography as the most promising research area for improved detection of early breast cancer in large-scale screening programs. Based on that recommendation, NCI established an International Digital Mammography Development Group (IDMDG), bringing together multiple leading academic and industrial institutions.[1] In addition, in early 1993, NCI staff developed and formulated the Federal Technology Transfer Program in Digital Mammography to identify and transfer digital imaging technologies originally developed for space, defense, intelligence, energy, and other communities to advance digital detectors, display systems, image analysis, transmission, and storage.[2] These extensive collaborations of multiple government agencies, industry, and academia facilitated comprehensive development and testing of digital mammography.

Encouraged by this experience, in early March 1996, the U.S. Public Health Service's Office on Women's Health (PHS OWH) established a Federal Multi-Agency Consortium for Imaging and Other Technologies to Improve Women's Health (Consortium) to expand technology transfer. The membership of the Consortium includes but is not limited to the Food and Drug Administration, Health Care Financing Administration, Central Intelligence Agency, Department of Defense, Department of Energy, and National Aeronautics and Space Administration. The activities of this Consortium have been critical for sharing expertise, resources, and technologies by multiple government agencies for the advancement of breast imaging technologies for early detection of cancer, such as digital mammography; magnetic resonance imaging (MRI); ultrasound; nuclear medicine and positron emission tomography; and related image display, analysis, transmission, storage and minimally invasive diagnoses and treatments.[3]

The first priority recommended by the Consortium was to establish, evaluate, and implement a comprehensive inventory of the government-wide technology transfer opportunities. In May 1996, the PHS OWH held a conference entitled "New Frontiers in Image-Guided Breast Cancer Diagnosis and Treatment" that developed recommendations on the current and future scientific needs and technologic challenges in breast imaging. Based on these recommendations, the PHS OWH developed a problem statement that translated clinical needs in breast imaging into generic technical specifications in order to establish a common vocabulary between the medical community and engineers, physicists, and other scientists working on the development of advanced technologies for defense, space, intelligence, energy, and other applications. This problem statement was distributed to over 300 academic and industrial laboratories in search of technologies that may advance the current state of the art in breast image acquisition, display, analysis, management, and transmission. As the result of these efforts, about 100 technologies have been identified and incorporated into the development of the technologic inventory. About 50 technologies, judged as promising in their potential to advance breast imaging by the PHS OWH staff and peer review, were selected for presentation at a public conference entitled "Technology Transfer Workshop on Breast Cancer Detection, Diagnosis, and Treatment" and sponsored by the Federal Multi-Agency Consortium. This workshop, convened on May 1-2, 1997, further facilitated technology transfer from DoD, CIA, DOE, NASA, and other agencies by fostering government-wide collaborations and public/private partnerships.[3] In addition, this Federal Multi-Agency Consortium meeting developed recommendations for the scientific and technologic projects critical for advancement of novel breast imaging.

Based on these recommendations, in June 1997, PHS OWH issued a competitive contract solicitation that supported high priority multidisciplinary research in the development and clinical testing of novel breast imaging technologies. By September 1997, PHS OWH funded the following projects in the areas of digital mammography:

1) **Optimization of Soft Copy Display Parameters for Digital Mammograms**
   Key Personnel: Shyh-Liang Lou, Ph.D., H. K. Huang, D.Sc., and Edward Sickles, M.D., of the University of California at San Francisco

2) **Computer Analysis of Mammography Phantom Images (CAMPI): An Application to the Optimization and Evaluation of a Full-Field Digital Mammography**
   Key Personnel: Dev P. Chakraborty, Ph.D., of the University of Pennsylvania

3) **Multi-Center Clinical Evaluation of Digital Mammography**
   Key Personnel: Etta Pisano, M.D., of the University of North Carolina and Martin J. Yaffe, Ph.D., M.Sc., and Donald Plewes, Ph.D., of the University of Toronto

The meeting of May 1997 clearly demonstrated that, while significant advances in the development of full-field digital detectors have been achieved, soft-copy display systems, although improved, remained the main roadblock to the clinical acceptance and implementation of digital mammography. Further extensive effort is required for the successful development, testing, and implementation of digital mammography displays and workstation design for image interpretation.

On March 9-10, 1998, in Washington, DC, the Public Health Service's Office on Women's Health and the National Cancer Institute convened a Joint Working Group on Digital Mammography: Digital Displays and Workstation Design. The meeting was attended by over 100 scientific leaders representing clinical practice, academic research, government agencies and laboratories, and medical imaging and display system manufacturers. This paper describes findings and recommendations of this working group.

Goals of the Joint PHS OWH/NCI Working Group

1) Review the state of the art of display technologies including current and future clinical applications and technical challenges.

2) Outline research priorities in digital display technology and workstation design requiring further support.

3) Identify technical limitations and develop a problem statement seeking new or emerging technologies.

The Working Group meeting consisted of the following sessions:

Session 1: Overview Session set a common vocabulary between multidisciplinary medical and other participants (e.g., defense, intelligence, space, energy, and other communities) and focused on the overviews of the current and future needs for digital mammography displays and their impact on clinical practice and patient care.

Session 2: The Session on Hardware for Soft-Copy Displays provided an understanding of not only the current state of the art but also anticipated technical developments in both CRT-based and flat panel display technologies. This session analyzed a gap between the clinical requirements for digital mammography displays and emerging technologies foreseeable on the market in the near future. An industry panel discussion in this session considered issues related to practicality, manufacturability, and cost effectiveness that will influence market demand and implementation of digital mammography display systems.

Session 3: The Workstation Design Session established a framework for the overall system design for image interpretation, including user needs, physical constraints (space, response time, etc.), hardware and software requirements, and overall system configuration. Scientific presentations further explored integration of image processing, computer aided diagnosis, and graphical user interfaces into a workstation design.

Evening Session: Working Group members met in the evening for a working session where they formulated consensus reports describing current state of the art and recommendations for the future priorities in research and development.

Session 4: The Human Perception Session addressed human visual perception as it relates to digital mammography displays and workstation design. The impact of human perception on display technical requirements were discussed, and the importance of psychophysical research emphasized.

Summary Session: During the Summary Session, co-moderators presented the consensus reports. The reports addressed (1) the current state of the art and fundamental clinical/technical roadblocks, (2) technical parameters required to meet current clinical needs, and (3) future priorities in technology development and related basic and clinical research.

Subsequent to the working group meeting, the session co-moderators, with input from their session participants, developed written summary reports. These summary reports have been incorporated into this article.

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Digital mammography is a technique for radiography of the breast in which the screen-film X-ray image receptor used in conventional mammography is replaced by an electronic detector.[1] The detector absorbs X rays transmitted through the breast and produces an electrical signal proportional to the intensity of the X rays. This signal is converted to digital format and stored in computer memory to form the image. A key feature of digital mammography is that image acquisition, display, and storage are performed independently, allowing optimization of each. The digital image is formed as a two-dimensional matrix of square picture elements (pixels) of a fixed size, typically 0.04 to 0.1 mm on a side.[2] Therefore, it is a sampled representation of the pattern of X-ray transmission through the breast. Within each pixel, the image takes on a single value representing the brightness of the image, averaged over the area of the breast represented by that pixel. Similarly, the intensity of X rays is sampled by an analog-to-digital converter into a finite number (2n) of levels, where n is referred to as the number of bits of precision to which the image is digitized. Typically, 12 to 14 bits of digitization are used, thereby producing 4,096 to 16,384 sampled intensity levels. Once the digital image is stored in computer memory, it can be displayed with contrast that is both independent of detector properties and adjustable by the viewer. This overcomes one of the greatest limitations of screen-film mammography—the fixed display scale, defined by the characteristic curve of the film.

Another important difference between screen-film mammography and digital mammography is that, in the former, the amount of radiation used to create the image is largely determined by the need for a screen to absorb enough energy to provide sufficient light to expose a film to the desired optical density. In digital mammography, the gain of the acquisition system can be controlled electronically and, therefore, the amount of radiation used can be chosen according to the required signal-to-noise ratio for the examination. This has implications for how optimum exposure techniques for digital mammography should be selected and provides opportunities for either improvement in image quality or else for dose reduction compared to screen-film mammography.

Types of Digital Mammography Systems

Currently, there are three types of dedicated digital mammographic systems under clinical evaluation. These are all based on a phosphor X-ray absorber and an optically sensitive photo-detector array that provides the image readout.

CCD-based area detector. The first practical systems for digital mammography were employed for producing small area (5 cm x 5 cm) digital images for guiding stereotactic breast biopsy. Such systems typically provide 1K x 1K images with 50 micron or 100 micron pixels. The detectors for these systems use an X-ray absorbing phosphor that is coupled to a smaller-area light-sensitive CCD array via demagnifying lenses or fiber-optic tapers. The CCD is a self-scanning device that provides an electronic readout of all the light-sensitive elements on a single wire. This output is then digitized to produce a high-resolution digital image. The CCDs are single crystalline silicon chips that typically cover an image field of less than 3 cm x 3 cm.

Although it is possible to use fiber-optic tapers with a greater demagnification factor to allow coverage of the entire breast, this is not a viable solution because it will result in very poor efficiency of transfer of the light to the CCD, resulting in a greatly reduced signal-to-noise ratio in the image. Instead, one company (Trex Medical) has built a detector for their digital mammography system that is formed as a large area X-ray phosphor coupled through 12 small-format modules, each consisting of a demagnifying fiber-optic taper and a small CCD. The sub-images from the modules are combined (stitched) in the computer to provide a single digital mammogram.

Amorphous silicon. Amorphous silicon provides another means for producing area detectors suitable for digital mammography. An array of photodiodes is deposited on a plate of amorphous silicon such that each element provides the signal for one pixel of the image. The diodes are covered by a suitable X-ray absorbing phosphor, such as cesium iodide, and the electric charges stored on the capacitance of each diode after X-ray exposure are read out through a network of switches and data lines. Another company (General Electric Medical Systems) has produced a digital mammography system employing this type of detector with 100 micron pixel size.

Scanned-beam detectors. An alternative approach to large area detectors is to use a detector that is long and narrow, which is scanned in synchrony with a slot-shaped X-ray beam, across the entire breast, to build up a full image. In this way, current photo-optical technology can be used to provide the required spatial resolution, dynamic range, and signal-to-noise ratio for digital mammography. Because the image is acquired sequentially in a scanning system, the acquisition time is longer than for an area detector and there is greater heat loading on the X-ray tube per image. An offsetting advantage of scanned beam systems, however, is that, because only part of the volume of the breast is irradiated at any one time, it is more efficient than area systems in controlling the detrimental effects of scattered radiation at the image receptor.

In the scanning system developed by Fischer Imaging, the radiation beam is confined to a "slot" of dimensions approximately 22cm by 10 mm at the detector. The detector is composed of several modules that are abutted end-to-end. Each consists of a strip of cesium iodide phosphor coupled to a time-delay integration (TDI) CCD array via a fiber-optic taper. Each CCD consists of a large number of columns and a smaller number of rows of light-sensitive elements. In TDI acquisition, as the detector is moved across the breast at constant speed, the charge collected in each element of the CCD, in response to the X-ray signal, is shifted down its column at the same speed as the scan motion, but in the opposite direction. When the charge packet reaches the last element in the CCD, the charge signals in the columns are read out. The image is acquired by scanning the fan X-ray beam and the slot detector across the breast in a direction parallel to the chest wall of the patient.

Clinical Applications

There are several clinical applications for which digital mammography can improve on the current state of the art with conventional film-screen imaging.

Near-real-time image display. This provides several advantages over conventional film mammography. (1) The time required between image acquisition and display can be reduced to a few seconds, compared to the approximately 5 minutes required for image processing of a conventional film examination, thereby potentially increasing patient throughput and reducing the per capita cost of examination. (2) Day-to-day variability in automated film processors, which now requires careful monitoring including daily sensitometry / densitometry measurements, also ceases to be a problem since film processing is eliminated. (3) Percutaneous biopsy and lesion localization procedures are facilitated by the ability to visualize, in a few seconds rather than several minutes, needles as they are positioned within or immediately adjacent to suspect lesions (this application, using a 5 x 5 cm field of view, is already built into several stereotactic-guidance mammography systems[3]). (4) With successful development of routine stereoscopic imaging, it may be possible to reduce or completely eliminate the need to perform recall mammography for summation artifacts (superimposition of normal breast structures, simulating breast masses), which account for up to one-third of recall examinations after mammographic screening.

Post-acquisition image enhancement. Signal processing techniques can be applied to the digitally acquired image to produce overall enhancement or to increase the conspicuity of specific mammographic findings. (1) Window and level controls can be manipulated, after image acquisition, to portray the entire breast with proper intensity and increased contrast, thereby providing a greatly expanded gray scale to facilitate visualization of important findings that otherwise might be obscured by display within the toe or shoulder of the characteristic film curve. (2) Enlargement (magnification) and unsharp masking techniques can make more readily visible such tiny structures as breast microcalcifications. (3) Other edge enhancement manipulations can highlight border contours in similar fashion to that produced by xeroradiography. (4) Noise suppression techniques can render more readily perceptible certain types of low-contrast objects, such as noncalcified masses having indistinct margins. (5) Intensity equalization techniques can be applied to clearly portray in a single image structures that usually are difficult to see on conventional film mammograms, such as the skin and subcutaneous tissues. (6) Digital systems also have the capability to overcome some underexposure and overexposure conditions and display fully interpretable mammograms despite what otherwise would be considered unacceptable image quality.

Image archival, storage, and retrieval. A major advantage of digital over conventional film imaging is its ability to conveniently archive, store, and retrieve images. This electronic archival process can permit substantial cost savings, especially for high-volume operations, despite the initial large expenditure for digital equipment. The cost of physical storage of films is eliminated, and personnel costs involved in image archival and retrieval are markedly reduced. Finally, digital data storage is much more rapid and reliable than film-based methods. This is particularly noticeable when prior studies are needed for comparison. Retrieval time is usually measured in seconds rather than minutes, hours, or days. Furthermore, one will only rarely encounter the situation in which digital examinations are misfiled, lost, damaged in storage, or signed out to another location.

Teleradiology applications. Electronic transfer of digital images to remote viewing sites can be accomplished almost as rapidly as occurs between the standard display workstation and computer storage. Numerous activities utilizing teleradiology have been devised, many of which are clearly applicable to mammography practice. (1) Radiologists who work in several different offices or hospitals will be able to monitor and interpret examinations that are carried out in a nearby or even distant location or locations. (2) Mammography screening in mobile units will be made more efficient not only by overcoming the need to transport films from the site of examination to the site of interpretation, but also by permitting image interpretation while patients are still available for repeat or additional exposures. (3) Teleradiology can be used to facilitate second-opinion interpretation, in effect making world-class mammography expertise immediately accessible to community-practice radiologists. (4) Digital image transmission can be the cornerstone upon which multisite teaching conferences are built, from applications as simple as the simultaneous conduct of teaching rounds among the nearby hospitals that participate in a residency training program to intercontinental multi-institution conferences supported by satellite transmission of digital mammograms.

Dual-energy subtraction imaging. Dual-energy subtraction mammographic techniques are based on the principle that, if both high and low kVp exposures are taken using the same radiographic projection, some breast structures will exhibit greater absorption of low-energy compared with high-energy photons, depending upon atomic composition. Thus, if there is no patient motion between exposures, one digital image can be electronically subtracted from the other, causing common elements (those that do not exhibit differential absorption) to cancel out completely. In this fashion, dual-energy subtraction mammography has the potential to increase the conspicuity of selected subtle findings, not only by showing some low contrast objects with increased clarity but especially by removing the superimposed “clutter” of background breast structures. This is particularly useful in demonstrating the tiny calcifications that can be the earliest indicator of a breast cancer, because the relatively high atomic number of calcium results in increased absorption of low-energy photons.

Tomosynthesis. In conventional tomography, the X-ray source and film move in opposite directions during exposure, so that radiographic features in only one plane of the image remain in sharp focus. However, conventional tomography of the breast is not practical since one exposure is necessary for each imaged plane, resulting in a high total radiation dose. Tomosynthesis involves exposures made as the X-ray tube moves in an arc above a stationary object (breast) and image receptor. Images must be obtained from multiple different angles to permit reconstruction of any plane in the breast that is parallel to the image receptor, but this can be accomplished with digital mammography at a total radiation dose similar to that of a single film mammogram. Recent development of a full-field digital detector that is flat now makes breast tomosynthesis practical in the clinical setting.[4] The ability to see through overlying areas of dense benign fibroglandular tissues may permit improved detection of early breast cancer and more accurate characterization of benign and malignant lesions.

Computer-aided image analysis. There already has been considerable success in developing computer-executed algorithms that detect abnormal findings on mammograms. Most such attempts have been directed at the identification of clustered microcalcifications, although several computer programs also have been written to detect spiculated breast lesions. Current applications are designed to indicate suspect findings by superimposing arrows, circles, or boxes in appropriate locations on digitized mammograms. The most successful of these programs presently are capable of identifying about 85% of targeted mammographic lesions, but also on average falsely indicate approximately one suspect area in each image.

If clinical utility is demonstrated (maintenance of essentially 100% sensitivity, especially if including poorly defined masses and densities), these computer-based applications will be widely used by radiologists as second-interpretation devices to avoid missing identifiable mammographic abnormalities. Especially if false-positive identifications are substantially reduced, this approach will be much less expensive than double readings done by another radiologist. However, it is unlikely that computer-aided detection (CAD) programs will be used in the United States for the first-pass interpretation of digital mammography screening examinations, sending only those cases with suspect findings on to a radiologist for definitive interpretation. This is because neither the providers of the CAD software nor the radiologists who use the software would be willing to accept potential malpractice related to missed cancers.

Computer-aided image interpretation programs also are being developed to further characterize already detected lesions, to determine whether subsequent management should involve biopsy or less invasive procedures. Again, these efforts have been directed principally at the analysis of clustered microcalcifications. Applications begin by quantitating the digital data within suspect lesions that already have been flagged either by radiologists or by computer detection programs. Formulas then are used to describe a wide variety of lesion characteristics; for calcifications these include not only the standard parameters assessed by radiologists (particle size, number, density, distribution, and shape) but also several more complex measures of calcific particle irregularity (for example, compactness, eccentricity, coefficient of convexity, elongation). Finally, numeric scores derived for these various parameters are weighted by pre-determined algorithms and combined to yield a likelihood of malignancy index, upon which management decisions can be based. Currently, the most successful of the calcification characterization programs operate at levels of diagnostic accuracy that usually approximate but occasionally even exceed those of expert mammographers. For other types of suspect lesions, today's computer-aided diagnosis programs are less fully developed.

Computer-aided instruction. Rapid, inexpensive, computer-based storage of digital mammography examinations facilitates the creation and utilization of computer-aided instruction packages, since selected sets of images can be readily catalogued and retrieved for display. The simplest application represents the digital counterpart to the conventional film mammography learning file. This involves an organized library of interesting case material (digital mammograms), supplemented by hard-copy text descriptions of mammographic findings, suggested interpretation, pathologic correlation, additional discussion, and literature reference material for each case or group of cases. Large numbers of mammography cases can be stored on a single optical disk. In a somewhat more sophisticated system, the text material itself is stored electronically, so that cases can be viewed with equal ease either in random sequence (as unknown cases) or in sequences organized either by diagnosis or by specific mammographic finding.

Instructional programs have been developed to provide the user with response-driven self-instruction modules, in which incorrect answers trigger the display of remedial material and additional questions before subsequent cases can be viewed.[5] Such systems can track the progress of individual users, compiling grades and documenting that proficiency has been achieved.

The most ambitious instructional packages will interface directly with the day-to-day interpretation of digital mammograms. Such systems would be activated at the request of the radiologist, whenever specific mammographic features are described by the radiologist or determined by a computer-aided characterization program. In either circumstance, a particular mammographic feature would call up related image and text materials from expert learning databases, to compare with the case under consideration. Thus, the radiologist could view pathology-proved cases in which mammograms display similar if not identical radiographic findings. Embedded text also could suggest strategies for further evaluation and interpretation of the mammographic findings.

Current Full-Field Digital Mammography Research

The manufacturers that developed each of the types of full-field digital mammography systems described previously have installed prototype units at several clinical sites (Table 1-1). A variety of investigational studies are currently being carried out at these sites, for a wide range of purposes. Studies designed to demonstrate degrees of safety and effectiveness of

Table 1-1. Clinical sites at which prototype full-field digital mammography units currently are in use for investigational studies

Equipment Manufacturer	Medical Center
Fischer Imaging	University of Toronto University of California, San Francisco University of North Carolina, Chapel Hill Brooke Army Medical Center Thomas Jefferson University
General Electric	University of Colorado University of Massachusetts Massachusetts General Hospital University of Pennsylvania
Trex Medical	University of Virginia University of California, Los Angeles Good Samaritan Hospital, Long Island

digital mammography compared to conventional film mammography are being conducted by each equipment manufacturer to secure approval from the Food and Drug Administration to market their devices for general use.

Of greater scientific value are more sophisticated studies being done at single sites or groups of sites, designed to assess the sensitivity and specificity of clinical images taken of the same women using both digital and conventional film mammography units. Such a large-scale screening trial is under way at the Universities of Colorado and Massachusetts, which will use ROC analysis to indicate the current capability of digital mammography in the detection of clinically occult breast cancer. A telemammography study is underway at the University of California San Francisco, designed to demonstrate whether digital mammography can successfully provide: (1) real-time consultation by off-site expert mammographers for on-site general radiologists conducting diagnostic mammography examinations and (2) accurate and time-efficient off-site interpretation and management by expert mammographers of diagnostic examinations simultaneously performed by on-site general radiologists using conventional film mammography. IDMDG also was assembled, involving many of the sites and all of the equipment listed in Table 1-1. Originally, NCI supported individual institutional clinical testing of digital mammography by the IDMDG. More recently, PHS OWH funded a 250-patient pilot study that has been undertaken by eight participating institutes of the IDMDG to facilitate multicenter clinical evaluation of digital mammography and its diagnostic value in high-risk women. This pilot research will be followed by a 2,500-patient study that will explore the accuracy of digital mammography in both screening and diagnostic settings. Results from the various scientific studies described above should be available in the next two to three years.

General Recommendations for Digital Mammography

For a number of reasons, the potential advantages of digital mammography can probably best be realized by interpretation from soft-copy display. Soft-copy display allows convenient and dynamic manipulation of the image display to obtain optimal presentation of information. In addition, there is the opportunity to eliminate the cost of hard-copy film and the associated time, complexity, and waste disposal problems of film processing.

Limitations of Current Display Workstations

Currently there are numerous impediments to the use of soft-copy display for digital mammography. These include deficiencies in the speed with which images can be loaded and presented on the display as well as inconvenience or inappropriateness of the human-computer interface of existing commercial systems. Most systems provide only rudimentary control of the lookup table, relating digital signal value and display brightness with such functions as linear clipping and scaling (window and level). More flexible lookup tables that provide nonlinear lookup tables are likely to improve image display and make more optimum use of the characteristics of the display device.

Generally, most displays do not have an adequate pixel matrix size to display the complete digital mammogram at full spatial resolution. There is also concern about whether the contrast resolution and display luminance of available hardware is adequate. There is controversy over this issue in that some scientists believe that performance of current systems is sufficient if image viewing takes place under appropriate conditions (e.g., very low ambient light).

Required Features of Display Workstations for Digital Mammography

The system should have the capability of displaying up to eight images simultaneously. These would include the standard four views of the breast for both the current and a previous examination. Image "hanging" should be automatic and customized to the preferences of the particular radiologist, with the possibility of override (moving or flipping images) when necessary. Images should load rapidly and it should be possible to retrieve other examinations from the archive quickly and efficiently, when it is desired to make comparisons.

The images should appear initially with a gray-scale rendition that is near-optimal, so that image interpretation can be accomplished with minimal need for user interaction in manipulating images. The viewer should be able to change the display characteristics easily when this is required.

The system should incorporate an image navigation strategy that provides convenient availability of the full degree of acquired spatial resolution of the images, while maintaining the anatomical context provided by an overview of the entire examination. Using overlays or another strategy, it should be possible to superimpose annotation information or CAD information on the mammograms and to black out nonanatomic information that may distract the radiologist.

To make full use of the digital nature of the images, the system should provide easy-to-use image manipulation tools, such as contrast, brightness, image reordering, selection of regions of interest, magnification, and other methods to provide quantitative measurements from the image. Since at least some type of hard-copy record may be required on occasion, the workstation should provide a preview of how any such printed mammogram would appear, so that the lookup table could be tuned to provide the most useful image before printing.

For practicality, the workstation must be compliant with the digital imaging and communications in medicine (DICOM) standard, and it should be possible to display digital mammograms from all DICOM-compliant acquisition systems, including those produced by other vendors. The workstation should be able to accommodate alternative acquisition schema that may provide complementary information (e.g., CAD, stereotaxy, tomosynthesis, digital subtraction angiography, dual energy subtraction, etc). Workstation design also should facilitate interfacing of the digital system with radiology/ hospital information systems (RIS/HIS).

The system should also support quality control functions for the digital mammography acquisition system as well as for soft- (and hard-) copy displays, and to facilitate quantitative use of digital image data for quality control testing. This would allow objective testing of imaging performance and could reduce some of the costs currently associated with quality control.

Research Priorities

Short term	• Develop improved quality control procedures for soft-copy displays.
Intermediate term	• Conduct performance-based studies on optimal technical parameters for digital displays, including contrast resolution, spatial resolution, display luminance, data compression, time efficiency, cost efficiency, accuracy, etc. • Improve display controllers to provide greater speed of image manipulation, application of nonlinear lookup tables, image zooming, and rehanging, etc. • Develop an improved understanding of design factors for the image reading environment. • Study how to optimize the human user interaction (ergonomics).
Long term	• Explore alternative display technologies. • Develop of education and testing methods to instruct radiologists in the use of digital display systems.

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Session 2: Display Hardware for Soft-Copy Display

Only direct-view display technologies capable of high brightness and high spatial resolution are considered to be candidates for mammography display. Projection technologies suffer from large space requirements and limitations to their dynamic range from veiling glare and ambient light. Head-mounted displays are not suitable, due to user fatigue and discomfort in prolonged daily use.

The principal candidate technologies for mammography image display are:

- Laser-printed film
- Cathode Ray Tube monitors (CRT)
- Liquid Crystal Displays (LCD)
- Field Emission Displays (FED)
- Organic Light Emitting Diode Displays (OLED)

Characteristics are summarized in Table 2-1.

Laser-Printed Film

Film has the combination of high spatial resolution, luminance, and contrast ratio that makes it the "gold standard" for display quality. Specialized laser film printers with 40-micron pixels are required to print digital mammograms with normal size. Conventional laser film printers with 80-micron pixels can display full detail by magnifying the image size. Luminance is effectively limited only by the intensity of the backlight. Mammographic film viewers are as bright as 1,000 foot-Lamberts (ft-L). Light transmitted through film has been measured at 520 ft-L. The contrast ratio of 800:1 ensures that limits of the human vision system and elsewhere in the imaging chain will determine the effective dynamic range.

The disadvantages of film are self-evident. It is a static medium that cannot take advantage of interactive image manipulation. More significant is the cost of producing and handling film images. Digital mammography introduces significant additional equipment costs, and savings related to film costs will be essential if the benefits of digital mammography are to be obtained by a broad segment of the American population.

Cathode Ray Tube Monitors (CRT)

CRT monitors are the reigning soft-copy display technology today. Manufacturing processes have been fine-tuned after years of volume production for the consumer entertainment and computer markets. Monitors with 5 million addressable pixels (2,000 x 2,500) are available from several manufacturers today; units nearing eight million pixels (2,500 x 3,000) are just beginning to appear commercially.

Maximum luminance and dynamic range of CRT displays are significantly lower than those of the conventional film-light box.[1-6] Peak luminance up to approximately 200 ft-L is available on 5-megapixel monitors today. Brightness levels as high as 400 ft-L have been achieved in experimental monitors. Typically, higher luminance is attended by degradation of the modulation transfer function (MTF), limiting the effective spatial resolution.

The MTFs of CRTs are anisotropic: whereas they reach values of 30 to 40% at the Nyquist frequency in the vertical direction, the MTFs are limited to 10 to 20% at the Nyquist frequency in the horizontal direction. The MTF in both directions is limited by the spot size and point spreading effects. These effects are nearly isotropic and increase in magnitude as luminance increases. The MTF in the horizontal direction is further limited by the bandwidth of the video electronics. Eight-megapixel displays today particularly suffer from degradation of the MTF in the horizontal direction, as the 800 megahertz bandwidth is difficult to achieve for the final stage of amplification, which drives the electron gun's grid. High luminance levels require higher output voltages from this final amplifier. Since high amplifier bandwidth is difficult to achieve at higher voltages, the requirement for high brightness further limits the achievable resolution on the CRT monitor.

The contrast ratio of CRT monitors is limited by veiling glare, which results primarily from scatter of light in the CRT's faceplate. Although a dynamic range of 10,000:1 can be demonstrated with measurements of uniform fields, the veiling glare imposes a limit on the dynamic range that can be displayed within any one picture to perhaps 200:1.[1-3] The contrast ratio of CRT monitors is further affected by ambient light, which reflects off the surface of the phosphor and raises the luminance in the "dark" or "black" portion level. This effect may be diminished by use of a darkened faceplate, but such faceplates reduce light output and require higher beam current for higher luminance at the

Table 2-1. Characteristics of current soft-copy display technologies

	Availability	Resolution (matrix size)	Luminance (ft-L)	Contrast ratio	Volume market drivers	Advantages	Problems
Laser-printed film	Now	4,000 x 5,000	520	800:1	Consumer, entertainment	Long familiarity, proven diagnostic capability	Operational cost, archive, communication
CRT	Now	2,500 x 3,000	120	200:1	Consumer, entertainment, computers	Relatively low cost	Noise, veiling glare
LCD	Year 2000 production, 8-bit, high fidelity monochrome	2,500 x 3,000 or more	>500	300:1	Laptop and desktop computers	Low glare, low reflection	Contrast dependent on viewing angle
FED	Year 2000–2002; experimental	2,500 x 3,000 or more	?	?	Hand-held devices, automotive, consumer electronics	High brightness, wide viewing angle	Manufacturing process, noise
OLED	Year 2003–2008; experimental	?	?	?	?	Potentially high brightness, wide viewing angle	Operating life, materials

phosphor. Minimization of surface reflection requires use in a very dark room, which is often not practical in the clinical care setting.

Spatial noise characteristics of CRT monitors derive largely from phosphor granularity, which affects the threshold contrast for human observers.[6, 7] High-efficiency phosphors desirable for high luminance from a given beam current are usually mixtures of two components, which increase phosphor's granularity. Single-component phosphors such as P45 are therefore usually preferred for medical imaging applications.

The major drawback of CRTs is the fact that, even for the display of static images, a scanning electron beam is required, writing the information (the image) serially up to 70 times per sec onto the CRT's faceplate.

Liquid Crystal Displays (LCD)

Active matrix liquid crystal displays (AM-LCD) are a familiar component of laptop computers, which provide the volume market for the development of new technology and manufacturing processes. Similar to film, AM-LCD devices are transilluminated devices whose brightness is determined by the intensity of the backlight. Also similar to film, the AM-LCD can be manufactured to absorb ambient light and viewed in rooms with high illumination. However, previous available devices have had severe variations in brightness as a function of viewing angle, which can even lead to contrast reversal. Since medical image interpretation requires low contrast detection at many gray levels, this performance limitation has previously ruled out use of these devices for clinical diagnosis. The viewing angle problem is now well understood, and several recent developments have established much improved consistency as a function of viewing angle.

Most AM-LCD devices use a thin layer (about 5 to 10 µm) of nematic liquid crystal material with the molecular direction or director aligned in the display plane. Boundary layers (the alignment layers) are used to orient the molecules on one surface with a specific angular orientation. The angular orientation of the alignment layers are different for the front and back side (typically 90 degrees), such that a helical twist of the nematic liquid crystal is created (twisted nematic [TN]). To make a display device using this TN structure, a polarizing film is used to filter the light incident on the back side. The polarization direction then rotates by 90 degrees when traversing the TN material.

A second polarizing filter, oriented 90 degrees to the first, is then placed on the front side of the TN cell. The LC molecules distant from the boundaries can change their orientation when an external field is applied. A variation in transmission through the TN-LC cell is established by perturbing the orientation of the directors in the cell with an electric field and altering the orientation of the light polarization with respect to the front polarizing filter. The electric field for each pixel is controlled by active matrix thin film circuits commonly made from amorphous silicon transistors fabricated on glass substrates.

The viewing angle problem with conventional LCD devices results from the perturbation of the director orientation by the electric field being in the direction of the surface normal. At intermediate gray levels, the directors are tilted obliquely in the display plane, and the intensity of light transmitted becomes a function of the incident angle relative to the director orientation.[8]

For higher electric fields the director becomes predominantly normal to the surface and the light deflection is reduced. At certain viewing angles, the expected reduction in brightness reverses and an increase in brightness occurs.

Three notable approaches have recently been introduced to reduce the viewing angle artifact.[8]

- **Retarder films:** Negative birefringence films are placed at the entrance or at the exit (or both) of the LC structure.[14, 15]
- **Multidomain TN LCDs:** For each pixel, two, four, or more subpixels each with a different orientation in the alignment layers are employed.[10, 16]
- **In plane switching (IPS):** Electrode pairs are positioned on the side of the LCD pixel structure such that the electric field rotates the director in the plane of the display.[13]

Retarder films provide global correction but, because of the complex and varying director configurations, do not provide a full solution. Multidomain designs with two or four cells provide some averaging of the artifact and are being widely used in the new generation of wide viewing angle AM-LCD devices that will reach the market in late 1998. IPS is particularly attractive in that it resolves the artifact problem at its source by maintaining the director orientations in the display plane. Electric fields are typically provided by interdigitated electrodes formed on the entrance side of the structure.[8] A multitude of combinations or variations of these approaches are now being considered and have great potential for high fidelity applications.[10-12]

Essentially all AM-LCD devices currently manufactured provide full color images. These devices have additional color filter layers that degrade optical contrast performance and reduce brightness. Specifically, color devices have three TN cells for each pixel, with each cell covered by a different color filter. For high quality color, the narrow spectral bandpass of the filters is associated with low transmission. Operation of the device to produce shades of gray is done by setting each cell to a balanced brightness. However, substantially brighter gray levels can be achieved by eliminating the color filters with the added benefit of a threefold increase in the number of pixels and improved optical properties. Manufacturing of monochrome devices with large area, high pixel density, and square pixels will be important to utilize this technology for mammography.

Field Emission Displays (FED)

Field emission displays have phosphor screens behind which is a matrix of microvacuum cells such that each pixel has its own cathode.[19]

For most devices, the cathode consists of a large array of low work function emitter microtips.[17, 20] Electrons are accelerated through the small vacuum cell to impinge on the cathodoluminescent phosphor layer. FEDs are similar to CRTs in that electrons are emitted from a cathode and accelerated toward the phosphor through a vacuum cell. However, they typically form the image in a line scan and thus do not have the problems associated with raster scanned devices. They are notable for their high brightness capability and good emission characteristics (i.e., a Lambertian angular distribution with very good viewing angle attributes). Numerous companies (Pixtech, Micron, Canon, Raytheon, Candescent, FED Corp., Futaba, and Motorola) will fabricate FED devices in 1998 for applications in small mobile and avionic devices.

Several problems with FED technology raise questions as to whether high fidelity devices suitable for mammography are feasible. Pixel brightness variations resulting from electron emission nonuniformities and low reliability of the cathode have been reported for prototype designs. Low voltage phosphors consume less power but have low efficiency and rapid saturation due to high current density. However, the longer phosphor lifetime and lower driver costs of a high voltage phosphor are complicated by an increase in flashover risk, more stringent surface degasification requirements, a need for wider vacuum gaps, and high aspect ratio spacers. While significant problems exist, the large amount of industrial development occurring with these devices may eventually result in very high performance devices.[18]

Organic Light Emitting Diode Displays (OLED)

Among display technologies, electroluminescence represents an all-solid-state approach that provides the most direct conversion of electrical energy into light. Efficiency and performance characteristics depend strongly on materials and fabrication processes used. Electroluminescent displays (EL) use a phosphor under the influence of an electric field to generate light. Electroluminescence occurs in two forms: injection EL (light release upon recombination of minority and majority carriers), and high field EL (emission is due to impact excitation by accelerated charge carriers). Thin film EL devices are made up of a stack of conductors and dielectrics with a phosphor in the center. The thin films are deposited onto a glass substrate. A black thin film layer may be incorporated at the bottom of the structure to provide contrast enhancement. Thin film transistors can be used to address EL for high resolution, low cost devices.

Rapid advances have recently been made in the development of electroluminescent materials. Different doping elements have been used with a ZnS host, providing a wide range of emission spectra with typical efficiencies up to 5 lm/W (ZnS:Mn, ZnS:TbF3, ZnS:Mn, TbF3, SrS and CeF3). White monochrome emission can be obtained by mixing red-green and blue-green phosphors with high efficiencies. Another promising design concept has recently been reported consisting of a multilayer stacked structure with organic EL materials with increased efficiency and full-color capabilities.[21]

An attractive feature of thin film inorganic EL is the very steep luminance vs. voltage slope which occurs above a threshold. This, along with a fast phosphor time response, allows for a direct addressing of large arrays. The low voltage threshold and similar steep curve characteristics that have been reported for organic EL materials are of particular note since inexpensive driver circuits may be employed.[22, 23] Organic materials with high luminous efficiency (up to 12 lm/W), low driving voltage requirements, and fast response times have recently been described. Needs for improved performance relate to chemical structure of organic thin films, organic - metal contacts, organic-organic layers interface, device structure, nonradiative recombination losses, and electrical degradation. Materials include complex metallic compounds with aromatic rings, such as anthracene. In early stages of development, organic EL presents electrical reliability issues such as electrochemical instabilities with formation of radical species, contacts degradation, encapsulation (needed because of air and humidity sensitivity), and low thermal tolerance.

The low voltage and high efficiency of the organic devices has made them of particular interest. Since they operate like an array of light-emitting diodes, they have been referred to as organic light-emitting diodes (OLED) displays. They are regarded as the technology having the most promising long range potential but requiring significant materials research.

Suitability for Digital Mammography

The state of the art of current display technologies is sufficient for soft-copy display in digital mammography, provided that software functions are provided to overcome limitations of:

- Spatial resolution
- Limited luminance
- Dynamic range.

Digital mammography examinations produce data sets immensely larger than can be presented or perceived at one time. A standard mammographic examination at 50 micron pixel size generates four images of 4,000 x 5,000 pixels each, each pixel comprising 10 to 12 bits. A screening study will usually be compared to a prior exam, and these eight images are the data set the radiologist must interpret.

It is not necessary to have displays showing 4,000 x 5,000 pixels for each image. Human visual acuity is limited by the density of cones in the retina's fovea: they are spaced at about 2 microns, resulting in an angular resolution of about 1 arc-min arc for the typical eye-lens.[24] At a viewing distance of 50 cm, the object resolution is then 121 microns. A total of 2,048 of these pixels add up to a vertical image dimension of 11.5 inches, little more than the typical size of a mammogram. To see finer detail than this on film, observers get closer, often with the use of a magnifying glass. An electronic magnifying glass or zoom feature can accomplish the same function just as effectively on soft-copy display, provided it is ergonomically designed and essentially instantaneous in operation.

While zoom and magnification functions can effectively overcome limitations of spatial resolution, limitation of dynamic range is more difficult to mitigate. Wide dynamic range contributes a richness of perceived information that cannot be recovered with gray scale window and level adjustments. High display luminance enables wide perceived dynamic range, particularly in the presence of ambient light.

Current display technologies for 2,500 x 3,000 images are suitable for digital mammography if computer graphic magnifications are employed, provided that such displays prove to have MTFs better than present 2,000 x 2,500 displays. Such a display in landscape format would allow two images to be displayed on each monitor and thus eight images on a four-monitor workstation.

Computer processing can help to overcome some display limitations. High frequency enhancement helps compensate for display MTF and different threshold contrast. Equalization of brightness near the skin line reduces the dynamic range required. Still, the limited contrast of devices may reduce observer performance in diagnostic mammography. Objective data on display performance for diagnostic tasks is lacking. Every practical image processing measure must be taken to compensate for the limited dynamic range of the soft-copy display device.

The suitability of the display technologies for digital mammography is summarized below.

Laser-printed film. The standard of image quality. Suitable for use from a clinical viewpoint, but not a viable long-term solution because of the cost and the operational issues of hard-copy imaging.

CRT monitors. Spatial resolution is adequate provided that proper magnification tools are provided by the workstation software. Brightness and dynamic range are limiting factors but can be partly overcome through image processing, including but not limited to enhancement of tissue visibility near the skin line. If the needed software functions are provided, modern high brightness monitors are highly likely to be sufficient for primary interpretation of digital mammography.

LCDs. Monochrome units with adequate spatial resolution will be available shortly. Luminance is very high, and contrast when viewed on-axis is better than CRT monitors. Its major drawback is the degradation of contrast ratio with increasing viewing angle. The extent to which this will affect diagnostic performance is unknown. High performance gray scale LCD technology is mature enough to be evaluated in comparison to CRT for mammography

FEDs and OLEDs. Both FED and OLED are promising technologies that offer potential for high brightness flat panel displays with wide viewing angle, when and if the present manufacturing and materials science problems are resolved. FED and OLED have demonstrated potential and should be encouraged as future alternative display technologies.

Research Priorities

Short term

- Conduct studies to determine the relation between the visibility of early signs of breast cancer and digital display performance parameters.
- Update the body of work related to CRT evaluation.
- Conduct new research to evaluate display technology (particularly new generation CRTs and LCDs) for mammographic imaging objectively.

Intermediate term

- Develop and test perception models appropriate for mammographic imaging to enable optimization of display characteristics without lengthy and prohibitively costly trial-and-error. Work should begin immediately, as development and testing may require a number of years.
- Correlate the short-term research proposed above with the development of these models.

Long term

- Develop high resolution display technologies providing high spatial and contrast resolution, high luminance, high dynamic range and wide viewing angle at reasonable cost.
- Research materials and device structures for new display technology:
  – Techniques for manufacturing FEDs
  – Long life, high luminance OLED materials.
- Monitor and assess advances in commercial display technology and potential spin-offs from nonclassified defense, aerospace, and intelligence developments.

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Session 3: Computer Software and Workstation Design

Current State of the Art

Over the past decade, substantial resources have been directed at the development of digital X-ray detection systems for mammographic imaging. Currently there are several companies with full-field-of-view digital mammography systems seeking FDA approval for marketing. In order to obtain this approval, manufacturers need to show equivalence in diagnostic accuracy and dosage between current screen-film technology and digitally acquired images printed onto laser film. However, it is anticipated that direct digital acquisition of mammographic data will ultimately offer more than just a replacement for screen-film technology. It is a technology that should lead to improved diagnostic accuracy. This is possible due to the fact that, unlike screen film technology, digital mammography uncouples the detection and display processes, allowing for manipulation of the image data to enhance the conspicuity of mammographic abnormalities prior to display. It is believed that, in order for the radiologists to take full advantage of the many potential computer manipulations of digitally acquired mammographic data, soft-copy display of images will be essential.

It appears that approval for marketing of full-field-of-view digital mammographic detection systems is nearly at hand. However, issues concerning soft-copy display of images from these systems are only beginning to be addressed and they present significant challenges. Issues include the enormous size of mammographic image datasets and the wide range of visibly detectable gray levels needed to appreciate minimal differences in X-ray attenuation between normal and abnormal breast tissue. In principle these issues are solvable; however, there are severe cost constraints on this market that may hinder research on solving these problems. Reimbursement rates for mammographic interpretation are low and often considered a loss-leader of radiologic imaging. As a result mammography is one the most efficiently run areas of any radiology department. The interpretation process with current screen-film technology has already been designed for the most efficient use of radiologists' time. Any soft-copy display technology will have to compete with this already highly efficient, cost restricted process. Radiology soft-copy display systems are only a fraction of a much larger global market for soft-copy displays and, unfortunately, mammography occupies only a small portion of the market for radiologic equipment. Hence the market forces to move this technology forward in mammography are weak. In sponsoring this workshop, the PHS OWH and the NCI have stepped forward to identify roles that NIH might take in helping to mature this technology toward its clinical acceptance and implementation. Session 3 of this workshop addressed the issue of workstation design, summarizing current state of the art, identifying gaps in understanding and technology, and prioritizing a research and development agenda.

Clinical State of the Art

Speed, simplicity, and intuitive image review are essential components of a clinically acceptable workstation for mammography. There are currently no soft-copy workstations that would be acceptable to radiologists as a replacement for today's film and light box technology for mammography. However, several existing laboratory systems are exploring and defining key features that will be important to the clinically acceptable soft-copy workstation.[6, 11, 14] There are two environments, screening and diagnostic, in which mammography is performed, and workstation designs need to take into account radiologists' needs in both environments.

In the screening environment, speed and ease of image review are of paramount importance. In this setting, two views of each breast (craniocaudal and mediolateral oblique views) from the current exam are compared to the same views from a prior year. Not infrequently, there is also the need to compare the current exam to multiple prior years. Thus, at a minimum, a soft-copy workstation must be capable of displaying at least eight different images (two views of each breast, current and prior). With current detector technology, this means that workstation must be capable of handling a minimum of 320 Mbytes of raw image data per examination. On a light box, the arrangement of films allows for symmetry comparisons between opposite breasts, confirmation of findings on both the craniocaudal and oblique views, and assessment of interval changes with prior exams. With current mammography film multiviewers, these eight projections can all be viewed at the same time, such that only simple head and eye movements are required by the radiologist to make these various comparisons.

The images are then reviewed a second time, using a magnifying glass to aid identification of microcalcifications and architectural distortion and to help characterize morphological features of soft tissue masses and calcifications. Although a lot happens in the review of a screening mammogram, the perceptual skills of the radiologists are highly trained at these tasks, and they can typically be completed in about one minute. Positioning of the next patient exam on the multiviewer takes a fraction of a second, and workstations will need to be able to handle near-instantaneous presentation of image data for the next patient.

In the diagnostic environment, speed and ease of use of the soft-copy workstation are similarly important.[2] However, film arrangement and manipulation are much more variable than in screening, and are likely to present more of a challenge to technology and system developers than will be required for the screening mammography workstation. Images that will require viewing will include the standard craniocaudal and mediolateral oblique views, prior mammographic exams, tailored mammographic views (e.g., straight mediolateral, magnification, spot compression, rolled, and implant displacement views), as well as images from other modalities (ultrasound, MRI), and new imaging techniques (digital tomosynthesis). Further complicating the display issue is that the same images will also need to be viewed subsequent to imaging processing used to enhance the conspicuity of specific findings (e.g., architectural distortion). Not only does the manner in which radiologists view all these images differ from radiologist to radiologist, but also for an individual radiologist the viewing pattern will vary from case to case. To replace the mammographic view box, workstations will have to permit the radiologists to navigate through hundreds of megabytes of data at speeds approaching those of the head and eye movements of the radiologist.

Technical Overview of State of the Art

Current state-of-the-art computer technology is believed to be adequate for implementation of functional, acceptable clinical workstations. Although the storage needs for a breast imaging exam will be greater than that of any other radiologic imaging technology, use of an optical disc, tape, and lossless data compression (3-5:1 ratios) will permit storage of several years of raw image data for any single patient. When needed these data can be transferred from storage media via high speed ATM and Gigabit Ethernet communication networks[8] into the workstation. Quick access to a large amount of data will be essential. Systems using large amounts of DRAM[7] or video RAM[14] have been designed to permit the radiologist to gain near instantaneous access to these large datasets. However, less expensive solutions, such as more direct data transfer pathways or software optimization for existing data transfer schemes could be implemented. Image boards that convert 12 and 16 bit data down to 10 or 8 bit data are currently on the market and will facilitate rapid data manipulation at the workstation. For image viewing, 2K x 2.5 K video monitors are currently being used in prototype digital mammography workstations, and with the proper image handling and manipulation tools are thought to be adequate for first generation workstations. The precise number of CRTs needed in a workstation requires further study. However, one[14] and two[6, 11] 2.0 x 2.5 K monitors have been used in prototype workstations for screening mammography.

As with other radiologic imaging modalities, standards have been developed for handling image and image related demographic data (DICOM [NEMA 97] and HL7 [HL7 94]). Use of these standards in digital breast imaging is obviously essential, as mammography workstation will need to tap into existing picture archiving and communication, radiology information, and hospital information systems. Prototype workstations that use these standards have already been developed that connect to existing PACS, RIS, and HIS.[9]

Despite the fact that current display technologies are considered adequate for the first generation of mammographic workstations, there are a number of technologies on the horizon that could markedly enhance soft-copy display, not only in mammography but radiology in general. These include such technologies as LCDs, which have a higher luminance than currently used CRTs, and 20 megapixel displays (as opposed to currently used 5 megapixel displays) which may come to the market in the future.

Image Preprocessing/Handling

Image processing is an area that is critical to the success of soft-copy workstations not only for mammography, but also for other projection radiographic techniques such as bone and chest.[13] Some of the issues are the same regardless of body part being imaged; others are specific to mammography. For soft-copy displays in general, it is important to define a "default image," which will have identical perceptual characteristics regardless of the system on which it is being displayed. This is important, as not only do CRT characteristics change from one manufacturer to another, but identical models of CRT's differ from one another as they come off the production line and as they are used. Thus, if the fidelity of the image is to be maintained so that it has an identical appearance regardless of the manufacturer or age of the workstation, workstation-specific processing will be necessary to achieve this.

Mammography-specific image processing includes methods for enhancing the conspicuity of pathologic findings. Unlike many areas of radiology, there are relatively few features that are used by the radiologists to detect and assess breast abnormalities. These include mass shape and margins, calcification morphology and distribution, and architectural distortion. Algorithms that enhance the conspicuity of these features hold great promise for increasing the sensitivity and specificity of mammography. In addition, one of the hoped for benefits of digital mammography is improved visualization of pathology in the mammographically dense breast. With current screen-film techniques, dense breast tissue is known to obscure even clinically obvious cancer. However, digital mammography permits image acquisition to be uncoupled from image display, allowing the acquired data to be manipulated in ways that may permit better assessment of the mammographically dense breast.

Other software techniques that will be critical to the success of mammography workstations is the use of "computer intelligence" to help the radiologist sort through the enormous amounts of data that digital acquisition and processing will present to the radiologists. This includes intelligent pre-hanging of individual images from a study, and perhaps intelligent strategies for navigating through the vast amounts of image data. These intelligent hanging and navigation schemes will need to take into account work flow that is common to all radiologists as well as the individual radiologist's specific work habits.

Integration of CAD with Workstation Design

CAD (computer-aided diagnosis) in mammography is the detection of a potential abnormality or the diagnosis of an abnormality made by a radiologist who takes into consideration the output from a computer analysis of the mammogram.[3, 4] CAD is being used to aid radiologists in both the screening and diagnostic mammography settings. Output from CAD programs include localization of potential abnormalities, indications of the likelihood of malignancy, and more controversially, quantitative risk assessment based on the mammographic density of the breast. Many observer performance studies have shown that the use of computer output improves radiologists' performance in mammographic detection and classification tasks.[1-10] However, integration of CAD into the daily practice of radiology is far from routine. One reason includes barriers to its easy use. Current programs are designed for digitized film mammograms, and the digitization process is cumbersome and time consuming. Direct digital mammography should greatly facilitate CADs use, and modifications to existing software to accommodate the image characteristics of direct digital data is not anticipated to be a significant barrier.

As a result of the potential impact of CAD on mammographic practice, design of soft-copy workstations will need to take into account how to efficiently implement the use of CAD in both screening and diagnostic workups. This includes interface design issues, such as when and how CAD output is used by the radiologist, and the form of that output (graphical, text, or both). As with other areas of workstation design, CAD needs to be fast and easy to use and will almost certainly need to accommodate user-specific preferences.

CAD and Observer-Controlled Post Processing

The theme of simplicity and ease of use for the interpreting radiologists will also need to guide the integration of signal post-processing into mammographic workstation design, as has been noted many times above. Once post-processing algorithms have been developed that highlight the conspicuity of specific mammographic findings, the method of controlling use of these algorithms and the presentation layout of resulting images will need to be carefully thought out and tested. In all likelihood, strategies to control the use of post-processing and layout presentation will be different in the screening and diagnostic environments.

One control strategy that is being contemplated is the use of CAD to guide the presentation of images based on the type of pathology that is identified by CAD. In the screening environment, high sensitivity is obviously desirable, although there is a direct relationship between the sensitivity and the number of false positives presented to the interpreting radiologists. Likewise, in the diagnostic environment, high specificity is desirable, but this comes at the expense of false negatives. Workstation adjustments for individual radiologist's sensitivity and specificity preferences will be necessary in both environments.

Regardless of any predefined strategy for controlling the use of post-processing algorithms and image layout, it is inevitable that some amount of user control will be necessary. Specific tools that radiologists will want to use will include those that permit rearrangement of images, image zoom-and-scroll, image magnification, image equalization, and near instantaneous application of pathology-specific enhancement algorithms. It is important to realize, however, that the clinically successful workstation will likely require minimal, if any, need for user controlled image manipulation for most cases.

User Interface and Reading Environment

Even with hardware and software that might realize the much hoped for improvements in diagnostic accuracy that digital mammography may offer, if radiologists' ability to get at this information is not intuitive and easy, clinical acceptance of this technology will be problematic. As with current screen-film and light box technology, the radiologists' attention and eyes need to be primarily focused on reviewing and assessing the images, not on manipulating and processing them. The clinically successful workstation will be one that packages all the necessary hardware and software components into a workstation that allows radiologists to spend their time looking at the images.[14]

Last, but not least, an understanding of the need to strictly control ambient lighting in the workstation area is needed. This is already a critical issue in mammographic reading rooms and will become more so if soft-copy workstations replace light box technology. Detection of subtle differences in shades of gray are essential to the identification of pathology in a mammographic image of the breast. Any level of ambient lighting in the reading area hinders the human eye's ability to detect these differences. Since current CRT technology cannot match the absolute luminance levels of film light boxes or the range of visibly detectable gray levels that can be achieved with current screen-film on light boxes, low ambient light levels in the soft-copy reading area will be even more critical than they already are to the detection and characterization of mammographic abnormalities.[2]

Research Priorities

Short term

- Model radiologists' viewing and work patterns in both screening and diagnostic environments so that critical parameters of work flow can guide workstation design. Time is an essential model variable.
- Develop image management and navigation software based on the above modeling.
- Define default soft-copy images (initial view and visually enhanced images) with respect to contrast resolution, spatial resolution, maximum luminance, background luminance, and system contrast. DICOM standards should be accommodated in defining default display performance.
- Develop CRT-specific compensations to permit fidelity of default images (i.e., default images should be the same regardless of specific display device). To achieve this, display specific processing needs to be studied to compensate for: absolute luminance, luminance nonuniformity, veiling glare, dynamic range, distortion, noise, modulation transfer, luminance range, and acquired image size.
- Use above findings and existing state-of-the-art technologies to assemble soft-copy workstations for digital mammography in both screening and diagnostic environments. Evaluate impact on diagnostic accuracy, time efficiency, cost, reader fatigue, and satisfaction of search in both screening and diagnostic environments.*
- Develop quality control techniques to assure fidelity of standard images regardless of specific displays.

Intermediate term

- Develop and evaluate feature specific enhancement algorithms (e.g., calcifications, masses, and architectural distortion).
- Further develop CAD algorithms for both the screening and diagnostic environments. Expand work on current algorithms to increase sensitivity and specificity and to decrease false positives. Modify current algorithms to accommodate direct digitally acquired mammographic data.
- Investigate user preference issues with respect to CAD and user directed image processing and manipulation tools.
- Incorporate above work on feature-specific image processing, CAD and user control issues into efficient and easily used soft-copy workstation. Evaluate impact on diagnostic accuracy, time efficiency, cost, reader fatigue, and satisfaction of search in both screening and diagnostic environments.
- Model and evaluate network support needed to incorporate digital mammography in full functioning radiology department.
- Evaluate utility, image quality, and methods of image compression for storage and data transfer.

Long term

- Research perception modeling and assessment techniques to more rapidly and less expensively evaluate new image processing algorithms and changes in soft-copy display technology (e.g., monitor brightness, monitors with higher and more uniform modulation transfer) on observer performance in radiology.
- Evaluate and incorporate new display technologies into mammographic workstations.

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*A few members in the working group felt that, if first generation workstations are evaluated without CAD, they may fail and, thus, incorporation and evaluation of CAD in first generation workstations is crucial.

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Session 4: Image Perception and Workstation Design for Mammography

This statement starts with a review of the sources of error in mammography. We indicate that at least half of the errors are due to faulty image perception. We then describe some of the principles of perception and show how understanding them can benefit mammography. The research that is needed to achieve these benefits is outlined. In the short term it is important to understand display system and environment tradeoffs that affect the detection and discrimination of abnormalities in mammography and to use this information to improve user interfaces. The long term goal is to develop predictive models that allow calculation of how to improve human performance by changes in images, detectors, displays, and the environment.

The Importance of Image Perception to Mammography

Mammography is a definitive diagnostic procedure. The mammographic exam whether it is film or digitally based is and will be the primary diagnostic procedure for breast cancer detection screening. Other imaging modalities such as MRI, ultrasound, or nuclear medicine are used primarily to aid in the diagnosis of breast cancer. A negative mammogram returns the woman to routine screening and a missed cancer becomes a missed opportunity for early treatment.

About half of the cancers missed at screening mammography are missed for perceptual reasons. The actual number of cancers missed in the usual clinical practice is unknown. Cancers can be missed because the imaging technique has failed to record them adequately or because the reader either does not see the cancer or sees it and decides that it is something else. These can be simply classified as technological, perceptual, and interpretational errors, respectively.

Bird et al.[1] analyzed 77 cancers that were missed during screening a population of about 77,000 women.[2] The results shown in Table 4-1 indicate that 43% of the misses were perceptual, meaning that the cancer was recorded in the image but not seen.

A review of 575 screening-detected cancers and 102 interval cancers found in the Canadian National Breast Cancer Screening Study showed that 46% of the screening-detected cancers and 34% of the interval cancers had a previous image that showed the cancer not reported on the initial reading.[3] The data are shown in Table 4-2.

There is also a very large variation in cancer detection performance among radiologists. Beam et al. gave 108 radiologists a mammography reading test consisting of 79 screening mammograms.[4] The results are summarized in Table 4-3. The median sensitivity of 80% indicates that on average 20% of the cancers known to be visible in the images were missed. In addition, note the wide variation in performance as shown by the minimum and maximum values.

These data indicate that observer error is an important issue for mammography and that methods for minimizing observer error should be incorporated into imaging systems. This is why so much effort has been put into CAD.

Table 4-1. Reason for mammographic false negatives in cases with a histological diagnosis of breast cancer within one year of screening from Bird et al.[1]

Reasons for Missed Breast Cancer	Number	Percentage
Misinterpreted	40	52
Overlooked	33	43
Suboptimal Technique	4	5

Table 4-2. Reason for mammographic false negatives in histologically proved cancers, Canadian National Breast Cancer Screening Study[3]

	Screen cancers		Interval cancers	
	No.	Pct.	No.	Pct.
Total number of cancers	575		102	
Total number of missed cancers	218		94	
Observer errors				
– One screen before detection	100	46	35	37
– Screen at time of detection	28	13	NA	
Technological errors				
– One screen before detection	28	13		
Occult at time of screening	62	28	59	63

Table 4-3 Summary measures of diagnostic accuracy among 108 U.S. radiologists reading randomly selected test set of 79 screening mammograms reported by Beam et al.[4]

	Median	Minimum	Maximum
Sensitivity %	80	47	100
Specificity %			
– Normal	95	37	100
– Benign	60	13	100
ROC Curve Area	0.84	0.74	0.95

The Perception of Information Displayed on a Workstation

The purpose of workstations is to transfer image information from the display surface to the human perceptual system.[5, 6] The efficiency of the transfer is influenced by (1) the matching of the physical properties of the display to the visual system, (2) the working environment, (3) the computer interface, and (4) the expertise of the observer.

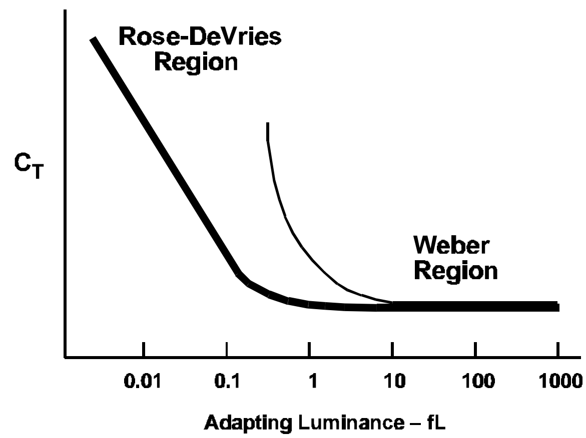
Matching the physical properties of the display to the visual system.

- **Image size and spatial resolution:** The effects of display size and pixel size on the detectability of abnormalities on mammograms have not been clearly determined. Mammographers typically use magnifying lenses when searching mammograms for microcalcifications. On a workstation this activity must be accomplished by a zoom and rove operation.

- **Image luminance and tone scale:** The ability of the visual system to detect a difference in luminance or contrast sensitivity has been extensively studied. It depends upon a number of factors, including the type of stimulus and the adapting luminance.[7] The basic situation is shown in Figure 4-1. When the adaptation luminance is low (the image and the environment is dark), the contrast threshold (C_T) changes rapidly with the luminance. This is called the Rose-DeVries Region after the two investigators who independently modeled contrast sensitivity when the eye was photon limited. At higher luminance levels the contrast sensitivity is independent of changes in the adapting luminance. This is called the Weber region after the investigator who first established this. The thick line shows the contrast threshold when the eye is fully adapted at each luminance. The thin line shows the contrast threshold in the darker part of the image when the eye is adapted at one level (10 fL in the diagram). When viewing a variegated scene with alternating dark and light regions, the eye can never fully adapt, especially to the dark areas. Consequently objects in the dark areas are harder to see.

- **Perceptually linearized gray scale:** One approach to improving contrast perception in the portions of the image where contrast sensitivity is increased is to adjust the gray scale in the image to more closely match the performance of the visual system. The idea is to produce a gray scale transfer function that converts equal changes in the digital input values to produce equal levels of perceived contrast over the entire luminance range of the monitor. This is done by modeling the human contrast sensitivity curve and using it to define a gray scale transfer function.[8] A perceptually linearized monitor yields better performance (detection of masses and microcalcification clusters in mammograms) than a monitor that has not been perceptually linearized. Krupinski and Roehrig compared performance when a monitor was linearized using the Barten curve versus performance with a default nonlinearized tone scale.[9]

Figure 4-1. Changes in contrast threshold relative to changes in the adapting luminance



Performance, as measured by ROC Az, was significantly higher when the monitor was perceptually linearized. Monitor luminance (80 fL Vs 140 fL) did not influence detection performance to a significant degree. Eye-position recording indicated that there may be some influence of monitor luminance on overall viewing time - average viewing times with the higher luminance monitor were shorter than with the lower luminance monitor. Tone scale had little influence on viewing time.

The working environment. The contrast on the display is due to both the light from the CRT phosphor and reflected light from the environment. The adaptation level of the eye is determined by the light from the display and extraneous light from other sources in the environment. It has been shown that excess light from unmasked portions of the display and the ambient illumination can decrease the detectability of microcalcifications on mammograms.[10] This effect is due to both loss of display contrast and decreased visual contrast sensitivity.

The computer interface. The arrangement of the images on the display, the use of image processing tools, and the control of the computer interface have not been studied carefully enough in mammography. The success or failure of a workstation may depend more on the way it functions than on the quality of the images. Time and motion studies are an important and efficient way to design proper and useful computer human interfaces.[11] These principles have been applied to workstations for other imaging applications.[12]

The expertise of the observer. Knowledge and experience clearly play a role in the interpretation of mammograms. Familiarity with the image content and the task influence diagnostic performance and the way that readers search the images. Krupinski found that readers with more experience tended to detect lesions earlier in search than readers with less experience; but readers with less experience tended to spend more time overall searching the images and covered more image area than those with more experience.[13] Nodine et al. also observed that experienced readers are characterized by speed and efficiency.[14]

Models for Image Perception

It is impossible to test clinically every change in an imaging system. The solution is to develop a model that will predict how system changes will affect performance. These models have the following form.

$$\text{detectability} = \frac{\text{(target properties)} * \text{(system properties)}}{\text{(system noise)}}$$

Decision theory models have been developed that relate the performance of an ideal observer on a specific task to the physical properties of the image.[15-17] Models can be used to predict how changes in the physical properties of the imaging system (contrast, unsharpness, noise) will affect performance. This type of modeling is currently being extended to include backgrounds that are very similar to those found in mammograms.

Measuring Observer Performance: Accuracy and Process

When comparing film versus workstation viewing of radiographic images, a number of factors relating to process and accuracy can be evaluated. The most important question that must be addressed is whether diagnostic accuracy using a workstation is at least as good as that when viewing film images. There are accepted measures of diagnostic accuracy that can and should be used in an objective assessment of observer performance. Although receiver operating characteristic (ROC) studies can be time-consuming and laborious, they do measure diagnostic performance reliably and they also permit valid statistical comparisons between viewing modalities. Other measures, such as sensitivity and specificity, and positive and negative predictive value are also accepted objective measures of diagnostic performance that can be derived without doing an ROC based study; however, they are biased by differences in the use of diagnostic criteria and by the prevalence of abnormality. Other measures and alternatives to ROC analysis (e.g., alternative forced-choice protocols) also exist and can be used as objective measures of observer performance. Subjective measures are useful and informative, but should not be used as the sole means of deciding whether one display modality is better than another. Subjective assessments of image quality should always be accompanied by objective measures of performance.

Measures of the process of reading images are also important because they are the determinants of efficiency and fatigue. These measures include viewing time, number of operations performed during viewing, times associated with viewing particular parts of a display, such as the time spent looking at the diagnostic image versus the menu on a computer display, and times associated with different diagnostic decisions. The time spent viewing various parts of the image and specific diagnostic decision times can be estimated from eye-position recordings.

Research Priorities

Short term

- Conduct psychophysical studies of the effect of display parameters on detection and discrimination of diagnostic features in mammograms:
  - Determine the effects of major display parameters on human detection and discrimination of diagnostic features in mammograms. This includes studies of spatial resolution, luminance, contrast range, system noise, ambient illumination and glare.
  - Phantom studies are appropriate, but the relationship between performance on the phantom and performance on real imagery must be established. It is highly likely that the most useful results will be derived from studies of hybrid images consisting of realistic backgrounds that have well-characterized abnormalities added to them.
  - Preference studies may be used in a complementary fashion but should not be used in lieu of objective metrics, such as receiver operating characteristic (ROC) parameters, forced choice parameters, observer signal-to-noise ratio measures, or sensitivity and specificity.
- Conduct time and motion studies on the performance of image reading tasks in mammography:
  - Develop models of the workflow of the radiologist during image reading tasks. Include as metrics the time to perform operations and the number of independent operations required to complete a task. The accuracy of models should be verified by comparison to the actual radiologist performance. Eye position studies can be helpful for defining where attention is directed during various tasks. These data will be useful for the system designer working on the display interface.

Intermediate term

- Determine the effect of image navigation and different display protocols on the detection and discrimination of diagnostic features in mammograms:
  - With film on an alternator, numerous images both present and past, can be viewed simultaneously in their entirety, and a magnifying glass can be used to detect microcalcifications. With monitors, the number of images displayed at full resolution is limited and a magnifying glass does not have the same effect with the monitor as with film because the actual pixels become visible. Some display protocols will be more fatiguing than others and may even affect diagnostic performance if they are too tedious and complicated.

Long term

- Develop computational models for predicting human detection and discrimination performance using real mammograms:
  - Testing every change in the physical parameters of an imaging system on decision outcome is not feasible. A predictive model would be much more useful, and scientific effort should be expended on model development.
- Study the effects of fatigue and vigilance during screening tasks:
  - In the general screening environment the detection of an actual lesion is a relatively rare event. Vigilance is required at all times by the mammographer in order to avoid missing these rare events. Although vigilance and fatigue have been well studied in areas such as the detection of targets using radar, the topic has not been studied well in radiology. The added factors of viewing images on a monitor and diverting attention from the diagnostic to the menu or other icons on the monitor may prove to be important factors.

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